BRIDGING THE TECHNOLOGY READINESS "VALLEY OF DEATH" UTILIZING NANOSATS

Robert A. Bauer, Pamela S. Millar
National Aeronautics and Space Administration Goddard Space Flight Center
Greenbelt, Maryland 20771
robert.bauer@nasa.gov, pamela.s.millar@nasa.gov

Charles D. Norton
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
charles.d.norton@jpl.nasa.gov

Abstract

Incorporating new technology is a hallmark of space missions. Missions demand ever-improving tools and techniques to allow them to meet the mission science requirements. In Earth Science, these technologies are normally expressed in new instrument capabilities that can enable new measurement concepts, extended capabilities of existing measurement techniques, or totally new detection capabilities, and also, information systems technologies that can enhance data analysis or enable new data analyses to advance modeling and prediction capabilities. Incorporating new technologies has never been easy. There is a large development step beyond demonstration in a laboratory or on an airborne platform to the eventual space environment that is sometimes referred to as the "technology valley of death."

Studies have shown that non-validated technology is a primary cause of NASA and DoD mission delays and cost overruns. With the demise of the New Millennium Program within NASA, opportunities for demonstrating technologies in space have been rare. Many technologies are suitable for a flight project after only ground testing. However, some require validation in a relevant or a space flight environment, which cannot be fully tested on the ground or in airborne systems. NASA's Earth Science Technology Program has initiated a nimble program to provide a fairly rapid turn-around of space validated technologies, and thereby reducing future mission risk in incorporating new technologies.

The program, called In-Space Validation of Earth Science Technology (InVEST), now has five tasks in development. Each are 3U CubeSats and they are targeted for launch opportunities in the 2016 time period. Prior to formalizing an InVEST program, the technology program office was asked to demonstrate how the program would work and what sort of technologies could benefit from space validation. Three projects were developed and launched, and have demonstrated the technologies that they set out to validate.

This paper will provide a brief status of the pre-InVEST CubeSats, and discuss the development and status of the InVEST program.

Figure 1: Artist's rendering of a 1U CubeSat in LEO

1. Introduction

While developing technology may seem somewhat straight forward to the technologist working in, say, a laboratory or clean room, who has a clear conception of the work underway and any future work needed to develop the device into its final operational form, describing the maturity of the development to management and stakeholders can be somewhat subjective and perhaps even overstated. Technology readiness within NASA dates back to the 1960's and was refined during the 1970's into the familiar figure of merit of Technology Readiness Level (TRL), a formal system to help unify assessments and descriptions of a technology's maturity [1]. The original scale conceived had seven levels, however, the generally used scale of today uses nine, with TRL 1 representing "basic principles observed," to TRL 9 representing "flight proven through mission operations." Subtle differences exist in the TRL scales baselined by different organizations, such as, ESA, the European Commission, the US DoD, or the oil and gas industry, but all still follow a similar progression of advancement - from basic idea, to a fully matured development that has been used in successful operations.

This paper addresses a subset of the overall TRL scale, particularly focusing on the advancement of technology beyond TRL 6. The classic technology infusion struggle is that any project manager desires that the new technologies to be incorporated into the project have their development risk sufficiently reduced so that neither the project's schedule nor budget will be impacted. On the other hand, the scientist or end user of the project desires the latest most capable technology possible that may maximize advances in their studies and opportunities for discovery. The technologist just wants to see their new device utilized in an operational system.

Within NASA's project development process, a project needs to complete mission-critical or enabling technology, as needed, to the level of a system/subsystem model or prototype demonstration in a relevant environment (ground, airborne, or space) (TRL 6 by KDP C/Preliminary Design Review) [2]. However, for many NASA missions, complex instrument development can become the primary key reason for project schedule delays [3]. As noted by Bitten, et al. in a study of cost and schedule growth of 40 NASA missions, instrument problems were found to be the largest contributor to project cost and schedule growth [4]. Multiple US Government Accountability Office (GAO) studies have determined programs that began with immature technologies experienced substantial cost growths. One such study reviewed 52 programs from space systems to torpedoes to SEAL delivery mini-submarines, and concluded that using immature technology led to an average (RDT&E) cost growth of 34.9%, while those with mature technologies had only experienced a cost growth of 4.8% [5].

The cost of furthering risk reduction is not a linear scale. For instance Mankins who not only popularized TRL assessment and helped spread the concept to other agencies, also cited another interesting observation - that the cost of achieving an incremental increase in TRL goes up dramatically with the TRL [6]. An internal ESTO model intended to be for illustration only and not representative of any specific instrument technology, has shown that the cost to advance from TRL 5 to TRL 6 is nearly four times more than the cost of all the previous TRL advancements combined. Advancing to TRL 7 is a significant maturation step beyond TRL 6, requiring an actual system prototype demonstration in the expected operational environment. With the even greater costs and rarer opportunities to test space-targeted technology in the operational environment, advancing technologies beyond TRL 6 is referred to as the *technology valley of death*.

2. Earth Sciences Technology Program

As the lead technology office with the Earth Science Division of NASA's Science Mission Directorate, the Earth Science Technology Office (ESTO) performs strategic technology planning and manages the development of a range of advanced technologies for future science measurements and operational requirements. ESTO technology investments attempt to address the full science measurement process: from the instruments needed to make observations to the data and information systems technologies to make those observations useful. ESTO's approach to technology development is end-to-end including planning technology investments through comprehensive analyses of science requirements, developing technologies through competitive solicitations and partnership opportunities, and making technologies available to scientists and mission managers for infusion. The technology program employs an open, flexible, science driven strategy that relies on competitive, peer-reviewed solicitations to produce the best technologies. In many cases, investments are leveraged through partnerships to mitigate financial risk and to expose the new developments to a broader user-base.

The ESTO program includes four distinct but related elements:

- Advanced Technology Initiatives (ATI) - provides for concept studies and development of component (Advanced Component Technology Program) and subsystems technologies for instruments and platforms.

- Instrument Incubator Program (IIP) - provides new instrument and measurement techniques including lab development and airborne validation.

- Advanced Information Systems Technologies (AIST) - provides innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products.

- In-Space Validation of Earth Science Technologies (InVEST) - provides for on-orbit technology validation and risk reduction for small instruments and instrument systems that could not otherwise be fully tested on the ground or airborne systems.

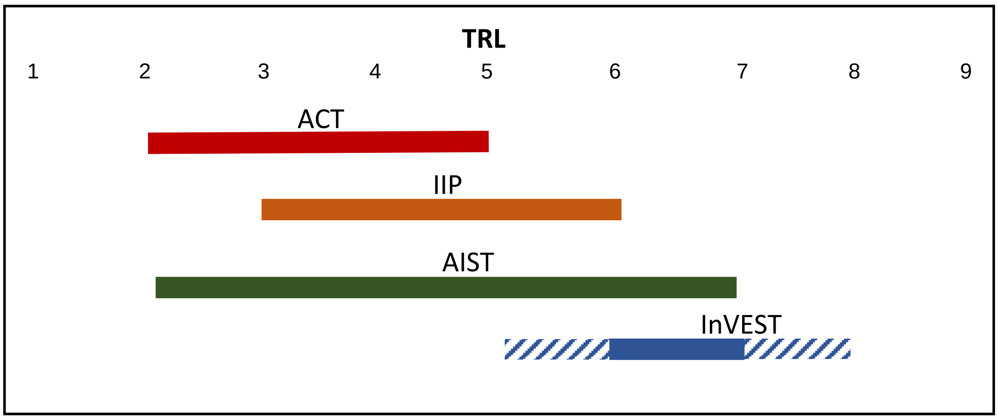

Figure 2: TRL ranges of ESTO's program elements

The first three ESTO programmatic elements generally advance technologies up to TRL-6. Given recent and rapid advancements in small satellites (including CubeSats), increased access to space, emerging standards, and cost effectiveness, ESTO is now pursuing mechanisms to flight qualify various technologies through successful spaceborne demonstrations to TRL 7 and/or 8. As non-validated technology is generally acknowledged as a primary source of mission delays and cost overruns the fourth element for technology flight validation directly addresses this concern.

3. Technology Validation via CubeSats

ESTO's initial approach to in-space validation of technology was based on identifying existing technologies that could significantly impact Decadal Survey mission concepts, and that were sufficiently mature for rapid enhancement and integration into 1U (10 cm x 10 cm x 10 cm) and 3U (30 cm x 10 cm x 10 cm) CubeSats [7]. The payloads were developed by existing ESTO Principal Investigators, whom also led the efforts, with spacecraft bus design, development, and integration led by university partners with significant experience in CubeSat development. The launches were acquired via the competitive NASA CubeSat Launch Initiative (CSLI) where NASA Launch Services identifies launch integration and test requirements, mission readiness reviews, and launch vehicle integration.

Figure 3: M-Cubed/COVE-2 is the reflight of a 1U CubeSat developed by U. Michigan to image the Earth carrying the JPL developed COVE technology validation experiment. Credits: NASA/JPL

Three of these projects were developed, launched, and have since demonstrated the technologies integrated into each [8]. The first one was the Michigan Multipurpose Minisatellite (MCubed-2) CubeSat, a collaboration between JPL and the Univ. of Michigan, launched in December 2013 as a secondary payload aboard National Reconnaissance Office Launch-39 (NROL-39) on an Atlas V. The 1U CubeSat validated an algorithm and processor technologies for the Multiangle Spectropolarimeric Imager (MSPI), a candidate instrument for the Aerosol-Cloud-Ecosystems Decadal Survey mission concept. The payload was the JPL-developed CubeSat On-Board Processing Validation Experiment (COVE) - a polarimetry data processing algorithm implemented on a new radiation-hardened-by-design FPGA (the first production Xilinx Virtex-5QV to fly in space) that was the basis of a previous advanced information systems award. This technology could reduce the future MSPI data downlink requirements by two orders of magnitude. One week after launch, an auto-run sequence using stored imagery was executed and validated against known results. Afterwards, COVE was further validated against the ground-based testbed using imagery taken by the MCubed-2 camera, completing all Level-1 requirements. In the following months, COVE continued to acquire and process sufficient imagery to characterize the performance of the hardware and software over extended temperature fluctuations, radiation, and longer acquisition periods. MCubed/COVE-2 operated successfully for 7 months. The validation experiment was run 30 times, all with expected results, using the Xilinx Virtex-5QV (rad-hard by design) FPGA and demonstrating that 2 orders of magnitude data rate reduction was achieved.

The second was IPEX, the Intelligent Payload Experiment that was also a 1U CubeSat developed by Cal Poly San Luis Obispo and JPL which launched with MCubed-2/COVE on NROL-39. IPEX validated autonomous science and product delivery technologies supporting TRL advancement of an information systems technology, the Intelligent Payload Module (IPM), which is targeted for the proposed HyspIRI Earth Science Decadal Survey Mission by providing a twenty-times reduction in data volume for low-latency urgent product generation for high data rate thermal infrared imaging and visible to near-infrared spectroscopy instruments. The IPM is an onboard processing system intended to intelligently decide which data to downlink when, in order to maximize the utility of HyspIRI's direct data broadcast system. The IPM software is capable of not only recognizing the features of interest, but also of reprogramming the CubeSat to target areas of interest for future data gathering and only downlinking the data that are relevant. IPEX operated over 10 months (exceeding 6 month target) and validated over 50,000 image products generated with near continuous autonomous operations. Feature detection, classification, and machine learning algorithms were run with a 100% success rate and will be infused into future beyond LEO CubeSat autonomous processing missions. A 20x data rate reduction was demonstrated via the onboard data products produced. A commercially available Gumstix computer-on-a-module validated high performance low-power payload processing.

Figure 4: GRIFEX 3-U spacecraft. Credits: NASA/JPL

The third was the GEO-CAPE Read Out Integrated Circuit (ROIC) In-Flight Performance Experiment (GRIFEX). It is a 3U CubeSat designed to verify the spaceborne performance of a state-of-the-art 128 X 128 ROIC in 180 nm CMOS focal plane array with 60 micron pixels, and has a 14-bit ADC in each pixel operating at an unprecedented rate of 14 kHz using only 1.1 W of power. The spacecraft is 10 cm x 10 cm x 30 cm in volume, weighs 3 kg and uses 6 W of power. It was launched as an auxiliary payload to the Soil Moisture Active Passive mission on a Delta-2 launch vehicle on January 31, 2015 and on February 11, 2015 the first set of analysis data and imagery were down linked from orbit. The technology specifically targets the requirements of the GEOstationary Coastal and Air Pollution Events (GEO-CAPE) mission concept. The ROIC is based on a 2008 Advanced Component Technology investment. Once validated, this technology could enable a mission like GEO-CAPE to make hourly high spatial and spectral resolution measurements of rapidly changing atmospheric chemistry and pollution from geostationary Earth orbit. GRIFEX was designed, built, tested and integrated for JPL by the students of the University of Michigan Exploration Laboratory (MXL). ESTO-funded operations concluded in June 2015 after successful validation of the technology; the project is still operating in an extended mission phase.

4. In-Space Validation of Earth Science Technology (InVEST)

After successfully demonstrating that technologies could be validated at a reasonable cost using the CubeSat platform, a pilot program was initiated and a competitive solicitation was released with proposals due in November 2012. The primary goal of the InVEST-12 program was to ensure future Earth science missions have access to spaceflight-validated advanced technology sensors and instruments that reduce risk, cost, and development time for Earth observing instruments and enable new observational measurements by technology maturation through on-orbit validation. Proposer's instrument subsystems or small instruments had to be at a Technology Readiness Level (TRL) 5 or 6 upon entry to the program. Funding was for developing the form, fit, and function of the technology to the spaceflight environment, launch, operations and post-flight evaluation of the demonstration only. Five awards were made and the key technology validation of each are summarized in Figure 3 below.

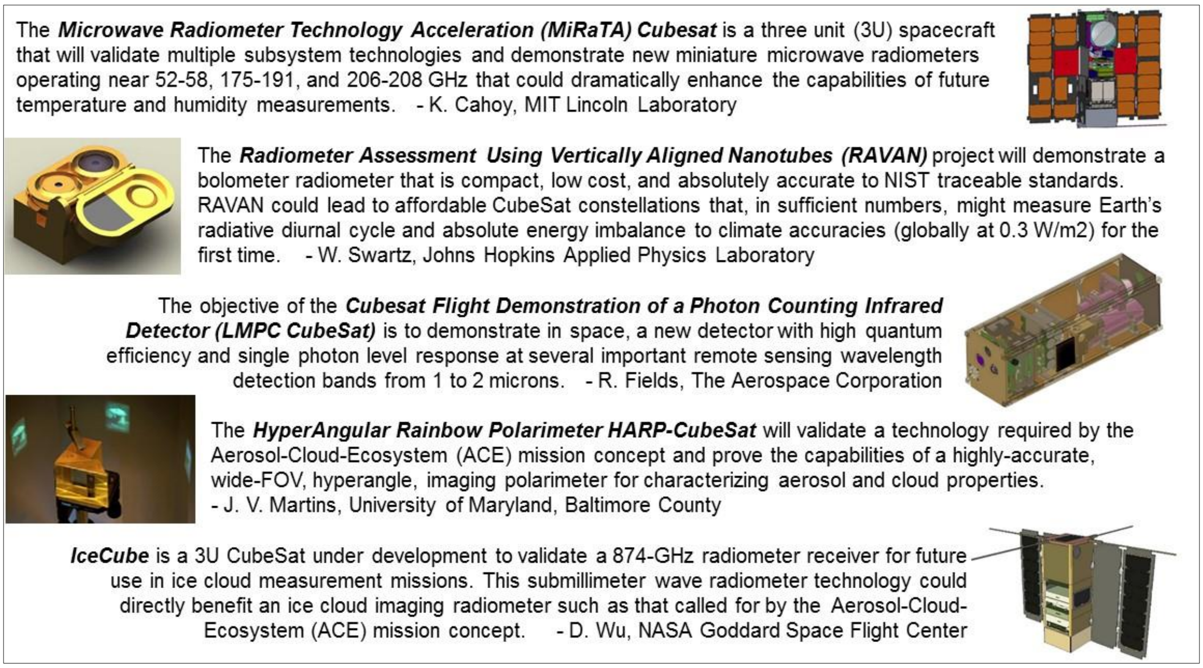

Figure 5: Summary of InVEST-12 selections

The technologies in four of these awards involve passive radiometry and sounding measurements (MiRaTA, RAVAN, HARP, and IceCube). The fifth (LMPC) also has a passive payload (IR detectors), but will be illuminated by a laser from the ground. These tasks are all under development at this time and are generally completing the second year of their three year awards. Each award is cost-capped and is valued at less than $4M each. Launch dates are anticipated in the 2016-2017 time period.

A second InVEST solicitation was issued in early 2015. As with the InVEST-12 call, proposer's instrument subsystems, small instruments, or any relevant information systems technology had to be at a TRL 5 or 6 at the time of proposal submission. The call allowed for CubeSats up to 6U in size to be proposed. The intent of the solicitation was for technology maturation through on-orbit validation only, so no funding will be provided for *new* technology development. The status of the InVEST-15 call as of this paper submittal is that proposals have been peer-reviewed and an announcement of selections is anticipated no later than the end of September 2015.

5. Conclusion

Introducing new technology developments into flight missions is a two edged-sword. On one side, new technology is what enables new capabilities and new measurements that can bring about new discoveries in Earth system science. On the other side, advanced technology inherently brings increased risks to the new project that can expand a project's schedule, and thereby, increase overall project costs. Maturing technology as far as possible is needed to help reduce this risk, and doing this in the least expensive way is always desired.

In NASA's Earth Science technology program, utilizing the CubeSat platform has been demonstrated as a viable path to accomplish this. Three initial tasks demonstrated the basic concepts that using the CubeSat platform could work for validating technology in the space environment and thereby bridging the technology valley of death by advancing the TRL beyond 6 at reasonable costs. A follow-on pilot program was initiated that resulted in 5 more CubeSat projects each of a 3U size. These projects promise to show further technology validation, and some even anticipate making some initial science quality measurements.

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